The Radio Afterglow and the Host Galaxy of the X-Ray Rich GRB 981226

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ABSTRACT

We report the discovery of a radio transient VLA 232937.2−235553, coincident with the proposed X-ray afterglow for the gamma-ray burst GRB 981226. This GRB has the highest ratio of X–ray to γ-ray fluence of all the GRBs detected by *BeppoSAX* so far and yet no corresponding optical transient was detected. The radio light curve of VLA 232937.2−235553 is qualitatively similar to that of several other radio afterglows. At the sub-arcsecond position provided by the radio detection, optical imaging reveals an extended R=24.9 mag object, which we identify as the host galaxy of GRB 981226. Afterglow models which invoke a jet-like geometry for the outflow or require an ambient medium with a radial density dependence, such as that produced by a wind from a massive star, are both consistent with the radio data. Furthermore, we show that the observed properties of the radio afterglow can explain the absence of an optical transient without the need for large extinction local to the GRB.

Subject headings: gamma rays: bursts; radio continuum: general; shock waves

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1.   Introduction

GRB 981226 was detected by the Gamma-ray burst monitor and the Wide Field Camera (WFC) on the *BeppoSAX* satellite on 1998 December 26.41 UT (Di Ciolo et al. 1998). The 6′ error radius of the WFC was further refined to 1′ by the *BeppoSAX* Narrow Field Instruments (NFI circle) which observed a fading X-ray transient 11 hours after the burst (Frontera et al. 1998). The primary interest in this burst is its apparent X-ray richness: the burst has the highest X-ray to γ-ray fluence ratio (Frontera et al. 1999) to date.

The 1-arcmin NFI error circle was intensively followed up by nearly half a dozen telescopes around the world. However, none of the proposed candidates have been reliably established to be the optical afterglow of the burst. Here we report radio observations of the NFI error circle. We have identified a transient radio source with properties similar to previously studied radio afterglows. We propose this to be the radio afterglow of GRB 981226. With subsequent optical observations we have identified a galaxy at the position of the radio source, presumably the host galaxy of GRB 981226.

2.   Observations

Radio observations began at the Very Large Array (VLA) on 1998 December 27.0 UT, 14 hr after the burst. At that time only a preliminary WFC position was available (Piro 1998) and we imaged, in the 4.86-GHz band, the entire 8-arcmin WFC radius error circle using a four-pointing mosaic; see Table 1. When the more accurate NFI position was released (Frontera et al. 1998) we began to image in the 8.46 GHz band. Synchrotron self-absorption is important at early times and for this reason it is advantageous to conduct the initial observations at higher frequencies (Shepherd et al. 1998). However, offsetting this advantage is the fact that the field-of-view is inversely proportional to the frequency; for the VLA the FWHM=$45'/\nu$(GHz) or 5.3′ at 8.46 GHz.

All observations were performed using the VLA in its standard continuum mode. At each frequency the full 100 MHz bandwidth was obtained in two adjacent 50-MHz bands. The flux density scale was tied to the extragalactic sources 3C 48 (J0137+331) or 3C 147 (J0542+498), while the array phase was monitored by switching between the GRB and a VLA phase calibrator J2333−237. Data calibration and imaging were carried out with the *AIPS* software package.

In our image of 1999 January 3.95 UT we found an unresolved source at high significance (6σ); see Figure 1. The source located at (epoch J2000) $\alpha = 23^h29^m37.21^s$

$(\pm 0.03^s)$ $\delta = -23°55'53.8''$ $(\pm 0.4'')$ is well within the NFI error circle; we refer to this source as VLA 232937.2−235553. In Figure 2 we present a light curve of the flux density measured at this position. For comparison, we present the light curve of another source, VLA J232940.0−235254, located well outside the NFI circle. From Figure 2 we see that VLA 232937.2−235553 is clearly a variable source. Quantitatively, this is revealed in the χ^2 obtained under the assumption of a constant flux density: the reduced χ^2 of VLA 232937.2−235553 is 5.7 whereas it is 0.7 for VLA J232940.0−235254.

3. Discovery of the Radio Afterglow

The radio light curve of VLA 232937.2−235553 is qualitatively similar to previous radio afterglows, most notably GRB 980703 (Frail et al. 1999). Although GRB 980703 was an order of magnitude brighter, it too showed a rise to maximum about 10 days after the burst, followed by a power-law decay to a level where it was no longer visible. It is on the basis of these similarities and the discovery of a underlying galaxy (see §4) that we make the claim that VLA 232937.2−235553 is the radio afterglow of GRB 981226.

An unlikely (but not implausible) hypothesis is that VLA 232937.2−235553 is an active galactic nucleus (AGN). Indeed, if later observations show detectable emission from VLA 232937.2−235553 (and not attributed to emission from the disk of the host galaxy) then this hypothesis would be favored. In contrast, no late time re-brightening is expected in the radio afterglow hypothesis.

We now proceed with the hypothesis that VLA 232937.2−235553 is the afterglow of GRB 981226. The qualitative behavior of other radio afterglows can be summarized as follows: the flux at a given radio frequency (ν_R) rises as a power law $F_R(t) \propto t^{\alpha_r}$, reaches a broad maximum at F_m and then decays as $F_R(t) \propto t^{\alpha_d}$. The epoch of peak flux is frequency dependent, $t_m(\nu_R)$. In anticipation of our discussion in §6 we have carried out a fit to this model. Given the paucity of data we fixed $t_m(8.46 \text{ GHz}) = 8.5$ d, a value that is reasonable (Figure 2), although somewhat smaller than those of previous radio afterglows (e.g. Taylor et al. 1998, Frail et al. 1999). We obtain the following model $\alpha_r = +0.8 \pm 0.4$, $F_m(8.46\text{GHz}) = 173 \pm 27$ μJy and $\alpha_d = -2.0 \pm 0.4$ (overall $\chi^2 = 9$ with 8 degrees of freedom). The errors quoted on each parameter are 1σ assuming all other parameters are fixed; the covariance between parameters is not reflected in these errors. Choosing t_m a few days on either side of our value does not substantially change the fitted parameters. Parenthetically, we note that at $b = -71°$ the path length GRB 981226 takes through the turbulent ionized gas of our Galaxy is small and therefore strong modulation of the afterglow flux by interstellar scattering is not expected.

4.   Host Galaxy of GRB 981226

We observed the radio transient position with the Low Resolution Imaging Spectrometer (Oke et al. 1995) at the Keck II telescope on Mauna Kea on three nights in June 1999: June 11 UT (SGD, B. A. Jacoby), June 19 UT (B. Schaeffer, FC) and June 21 UT (L. Hillenbrand). In each case we obtained images in the R band with total integration time of 1400 s, 720 s and 3360 s respectively. After correcting for the bias and pixel variation (flat fielding) we registered the images and combined them to form the final image.

Using the USNO A2.0 catalog (Monet et al. 1998) we computed an astrometric plate solution to one of the images of June 11. The r.m.s. statistical uncertainty of the solution, computed from the 12 tie stars, is σ_{RA}=0.32 and σ_δ=0.17 arcsec. To obtain the total uncertainty relative to the radio transient position, we add these uncertainties in quadrature with the empirical uncertainty of σ_{RA}=0.17 and σ_δ=0.18 of the USNO-A2.0 astrometric tie to the International Celestial Reference Frame (Deutsch 1999). The position of the host galaxy (discussed below) is quoted with respect to the astrometry of this image. The photometric zero point was determined by observations of the standard star field Mark A (Landolt 1992) on 21 June 1999 which was a photometric night. In order to facilitate comparison of our photometry we note that star "A" at R.A.= 23:29:35.6 and $\delta = -23$:55:38.0 (J2000) has R = 20.81 $\pm$0.02.

In Figure 3 we show a 50×50 arcsec optical region centered on the position of VLA 232937.2−235553. We note an extended object, presumably a galaxy, 0.55 arcsec West and 0.41 arcsec South of VLA 232937.2−235553. We propose this object to be the host galaxy of GRB 981226. Despite the offset, the position of the radio transient and optical galaxy are consistent within the astrometric uncertainties. While there is visually an indication of extension beyond the seeing FWHM (=0.85 arcsec), the signal-to-noise in our Keck image is not sufficient to reliably produce a measure of the half-light radius. We find the magnitude of the putative host to be R = 24.85 $\pm$0.06 mag in an 1.1 arcsec aperture radius about the centroid. Uncertainties arising from the unknown color term (images were obtained in R-band only) have not been included. Both the apparent magnitude and the small extension for the proposed host are completely consistent with normal galaxies at $z \sim 1$ and beyond (see for e.g. Hogg & Fruchter 1999, Mao & Mo 1999).

5.   No Detectable Optical Afterglow

Searches for the optical afterglow emission were carried out by a number of groups independent of our radio effort and results reported in the GCN[8]. Given the important diagnostic value of multi-wavelength observations we now summarize the results of the optical efforts and then proceed in the next section to use afterglow theory to see if the existing optical upper limits and radio light curve provide any significant constraints.

No fewer than three candidates were proposed as the optical afterglow from GRB 981226 and their sky location can be found in Figure 1. Galama et al. (1998) reported a source within the NFI error circle that was seen in their R-band images but was not visible in the Digitized Sky Survey (DSS) taken in the UK Schmidt red filter. Follow-up R-band observations (e.g. Rhoads et al. 1998, Bloom et al. 1998, Schaefer et al. 1998) found no evidence for variability. The absence of the source in the DSS is likely due to the different filters employed for the two comparison images.

Castro-Tirado et al. (1998) proposed a second candidate in the NFI error circle. From preliminary photometry of J-band images taken at the Calar Alto 3.5-m they found evidence for variability between 1998 December 26.76 UT (J=19.4) and 1998 December 27.76 UT (J=20.5). Wozniak (1998) and Lindgren et al. (1998) did detect the object in the I and R bands, respectively, but they find no evidence for variability.

A third candidate identified by Wozniak (1998) appears to be a genuine variable (Bloom et al. 1998) but it lies well outside the NFI error circle (but inside the WFC) and thus its relationship to GRB 981226 seems remote.

The best upper limits to a possible optical transient were obtained by Lindgren et al. (1999) with data obtained at the 2.5-m Nordic Optical Telescope and the 1.5-m Danish Telescope. They report no evidence for significant variability in the NFI error circle down to a limiting magnitude of R$\sim$23 mag for images taken at 0.4, 1.4 days and 2.4 days after the burst. The correction for Galactic extinction in this direction ($l = 38°, b = -71°$) is small (A_R=0.06).

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[8]The GRB Coordinates Network (GCN) is a service to the GRB community run by Scott Barthelmy and Paul Butterworth and can be accessed at
http : //lheawww.gsfc.nasa.gov/docs/gamcosray/legr/bacodine/gcn_main.html.

6. Discussion

The primary interest in GRB 981226 is its X-ray richness (Frontera et al. 1999). This burst of 20-s duration was otherwise unremarkable (DiCiolo et al. 1998). In the currently accepted picture for GRBs, the initial burst is due to internal shocks of relativistically moving material ejected by a central object. The afterglow emission arises as the relativistic ejecta is slowed down by the surrounding gas. From an afterglow perspective, the most interesting aspect of this GRB is the short-lived radio afterglow. The time to rise to the peak flux of about 8 d is typical of almost all previously studied radio afterglows. The short duration of the afterglow is therefore mainly due to the fast decline. Below we discuss a number of afterglow models which can account for this rapid decline in the radio flux

We begin with the simplest model: a spherical burst expanding into a constant density medium (Sari, Piran & Narayan 1998). In this case the fits in §3 predict that the optical flux would have reached the maximum value of F_m (corresponding to roughly 18 mag) at epoch $t_O = t_m(8.46 \text{ GHz})(\nu_R/\nu_O)^{-2/3} \simeq 500$ s; here $\nu_R = 8.46$ GHz, and $\nu_O = 5 \times 10^{14}$ Hz. The expected flux at later times would then be $F_m(t/t_O)^{\alpha_d}$. In this framework we would expect no detectable optical flux at the epoch of the first deep R-band observations, $t = 0.4$ hr (Lindgren et al. 1999) unless $\alpha_d > -1.1$. Our fits to the radio light curve rule out such a shallow decay at the 2.3σ level, and thus the observations are consistent with this model without invoking extinction. However, a logical conclusion of this model is that the underlying power law index of the shocked electrons (in the forward shock) is then $p = 1 - 4/3\alpha_d \sim 3.7 \pm 0.5$ much higher than the 2.2–2.5 value inferred in most bursts (Sari, Piran & Halpern 1999). For this reason we are not in favor of this model.

Two models have been proposed to explain rapid fading at X-ray and optical wavelengths: jets (Rhoads 1999, Sari et al. 1999) and expansion into an ambient medium with a radial density dependence ($\rho \propto r^{-2}$), such as that produced by a wind from a massive star (Chevalier & Li 1999; see also Vietri 1997). Both these models are attractive because they can also account for the fast decline of the radio emission.

First we interpret the data presented here in the framework of the jet model as presented for the optical-radio data of GRB 990510 by Harrison et al. (1999).

In the jet model radio emission above the synchrotron self-absorption frequency is supposed to rise as $t^{1/2}$, reach a maximum and then, for epoch $t > t_{\text{jet}}$, start a gentle decline as $t^{-1/3}$; here t_{jet} is the epoch when the bulk Lorentz factor of the ejecta becomes comparable to the inverse of the opening angle of the jet. At a later epoch when the maximum frequency ν_m falls below the observing frequency, the radio flux is expected to plummet as t^{-p}; see Harrison et al. (1999) for a brief review and application to GRB

990510. The radio light curve is consistent with this picture if one uses parameters similar to that of GRB 990510, $t_{jet} \lesssim t_m(8.46 \text{ GHz}) \sim 8.5$ d and $p \sim 2.5$. The value of t_{jet} is not well constrained but the rise in the flux at early times as $\alpha_r = +0.8 \pm 0.4$ (consistent with spherical expansion) suggests that $t_{jet} > 5$ d.

The evolution of the afterglow emission at early times when the optical data were taken ($t < t_{\text{jet}}$) is indistinguishable from the spherical case detailed above, except that in the jet model the observed maximum in the radio flux of $173 \pm 27 \, \mu\text{Jy}$ is about a factor of two below the optical maximum at t_O. Here again, if we adopt a simple decay with $\alpha_d \simeq -1.2$ we find the early decay of the light curve is sufficient to render the optical afterglow undetectable at the epoch of the first measurement without requiring extinction within the host galaxy.

In the case of the wind-shaped circumstellar medium model, the afterglow emission is weakened as the relativistic blast wave ploughs into ambient material with decreasing density. Chevalier & Li (1999) have applied this model to the afterglow of GRB 980519. We find that for reasonable stellar wind parameters this model can fit the light curve in Figure 2. Extrapolating this model into the optical band at t=0.4 day (the epoch of the first observations by Lindgren et al. (1999)) we predict F_m=870 μJy at $\nu_m = 8 \times 10^{11}$ Hz, $p = 3$ and the cooling frequency $nu_c = 8 \times 10^{16}$ Hz. The expected R-band flux density in this model, given by $F_R = F_m(\nu_R \nu_m)^{-(p-1)/2}$, lies below the observed magnitude limit.

In summary, regardless of which model we use (spherical, jet, circumstellar), we find that we can explain the radio afterglow emission without invoking extinction to explain the absence of the optical afterglow. While we cannot rule out large extinction local to the GRB, it is not required. Unfortunately, the paucity of the data does not allow us to chose uniquely the two competing models. If this GRB was the end product of a massive star then the short duration of the radio afterglow could well be due to the blast wave running out of the dense circumstellar medium. Indeed, as noted from radio studies of type II SNe (surely the end products of massive stars), there is considerable structure in the distribution of circumstellar matter. Radio emission from a number of SNe shows undulations which can be ascribed to successive rings of material (Weiler et al. 1992) and in other cases the sudden cessation of radio emission (including 1987A) can be due to an edge in the circumstellar matter (Staveley-Smith et al. 1992, Montes et al. 1998). The above discussion highlights the growing and unique contributions that radio afterglow can make to the study of GRBs. In the future, high signal-to-noise radio observations of GRBs should be capable of showing whether the emission simply peters out or is reduced abruptly. If the latter then radio afterglow will allow us to probe the structure of the circum-burst medium.

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Table 1.   VLA Observations of GRB 981226

Epoch (UT)	$t - t_0$ (days)	ν_{obs} (GHz)	$S_{RT} \pm \sigma$ (μJy)	$S_{field} \pm \sigma$ (μJy)
1998 Dec. 27.00	0.59	4.86	105±48	
1998 Dec. 29.92	3.51	8.46	73±27	136±27
1998 Dec. 30.95	4.54	8.46	143±45	
1999 Jan. 03.95	8.54	8.46	169±28	114±28
1999 Jan. 07.98	12.57	4.86	−13±43	
1999 Jan. 07.98	12.57	8.46	67±29	178±29
1999 Jan. 11.06	15.65	8.46	80±30	140±30
1999 Jan. 16.09	20.68	8.46	−28±30	153±30
1999 Jan. 19.89	24.48	8.46	27±14	145±14
1999 Jan. 21.85	26.44	8.46	37±20	103±20
1999 Mar. 04.72	68.31	8.46	−14±19	132±19
1999 Mar. 05.93	69.52	8.46	−14±14	142±14
1999 Mar. 28.74	92.33	8.46	9±25	111±25
1999 May 27.44	152.03	8.46	15±20	133±20

Note. — The columns are (left to right), (1) UT date of the start of each observation, (2) Time elapsed in days since the GRB 981226 event, (3) The observing frequency, (4) The peak flux density at the position of the radio transient with the error, given as the root mean square flux density, and (5) The peak flux density of a comparison source in the field. The synthesized beam at 8.46 GHz is of order 4.5″ between 1998 December and 1999 January, while for observations in 1999 March the beamsize is 12″. The beamsize at 4.86 GHz was approximately 6.7″.

VLA 8.46 GHz   1999 January 3.95 UT

GRB 981226

-23 55 00

DECLINATION (J2000)

30

* C-T

56 00

VLA J232937.2-235553

30

* G

NFI

57 00

23 29 40   38   36   34   32
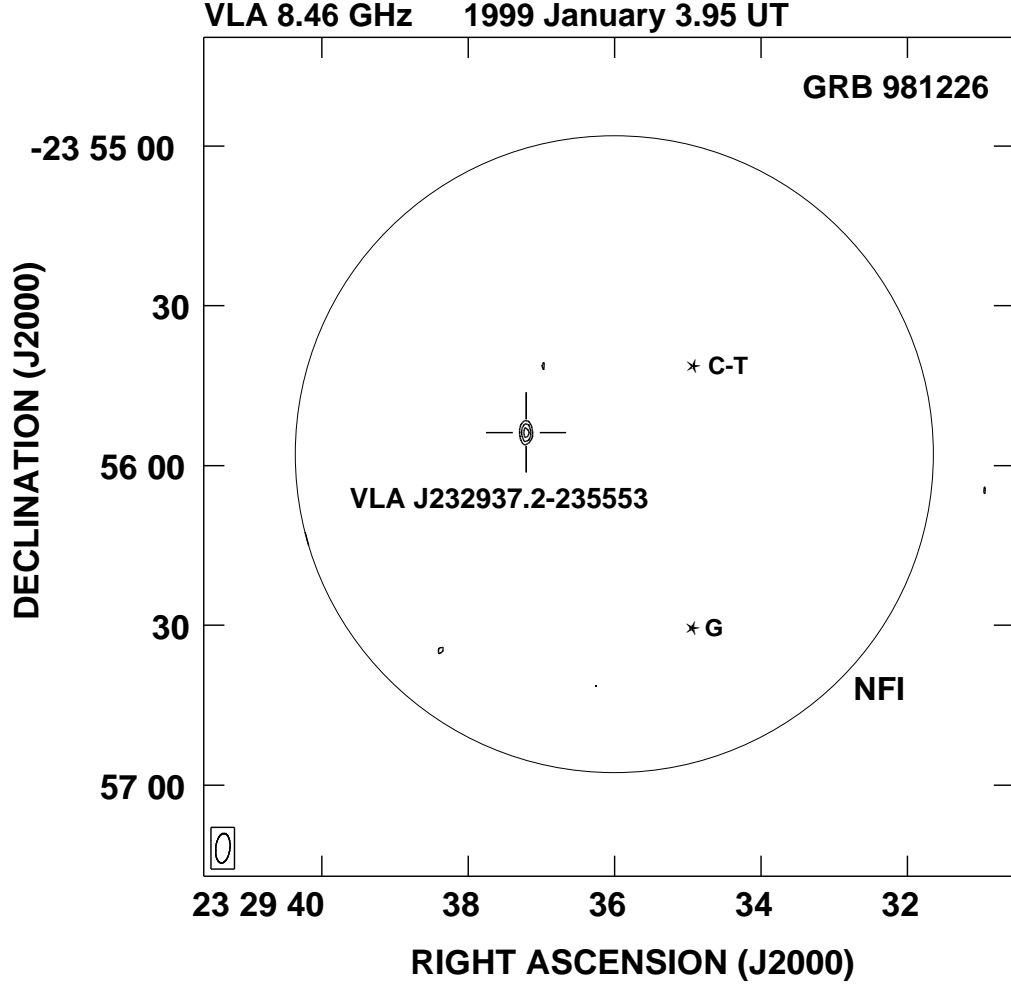
RIGHT ASCENSION (J2000)

Fig. 1.— An image of the field of the radio transient of GRB 981226, taken with the VLA at 8.46 GHz on 1999 January 3.95 UT. The arcminute error radius of the X-ray afterglow as detected by the NFI of *BeppoSAX* is indicated by the large circle. The radio transient (VLA J232937.2−235553) lies between at the center of the cross. Contours are plotted in steps of 3.5, 4.5 and 5.5 times the rms noise of 28 μJy/beam. The shape of the $5.6'' \times 2.7''$ beam in shown is the lower left corner. The two asterix symbols indicate the position of the optical afterglow candidates proposed by Galama et al. (G) and Castro-Tirado et al. (C-T). See text for more details.
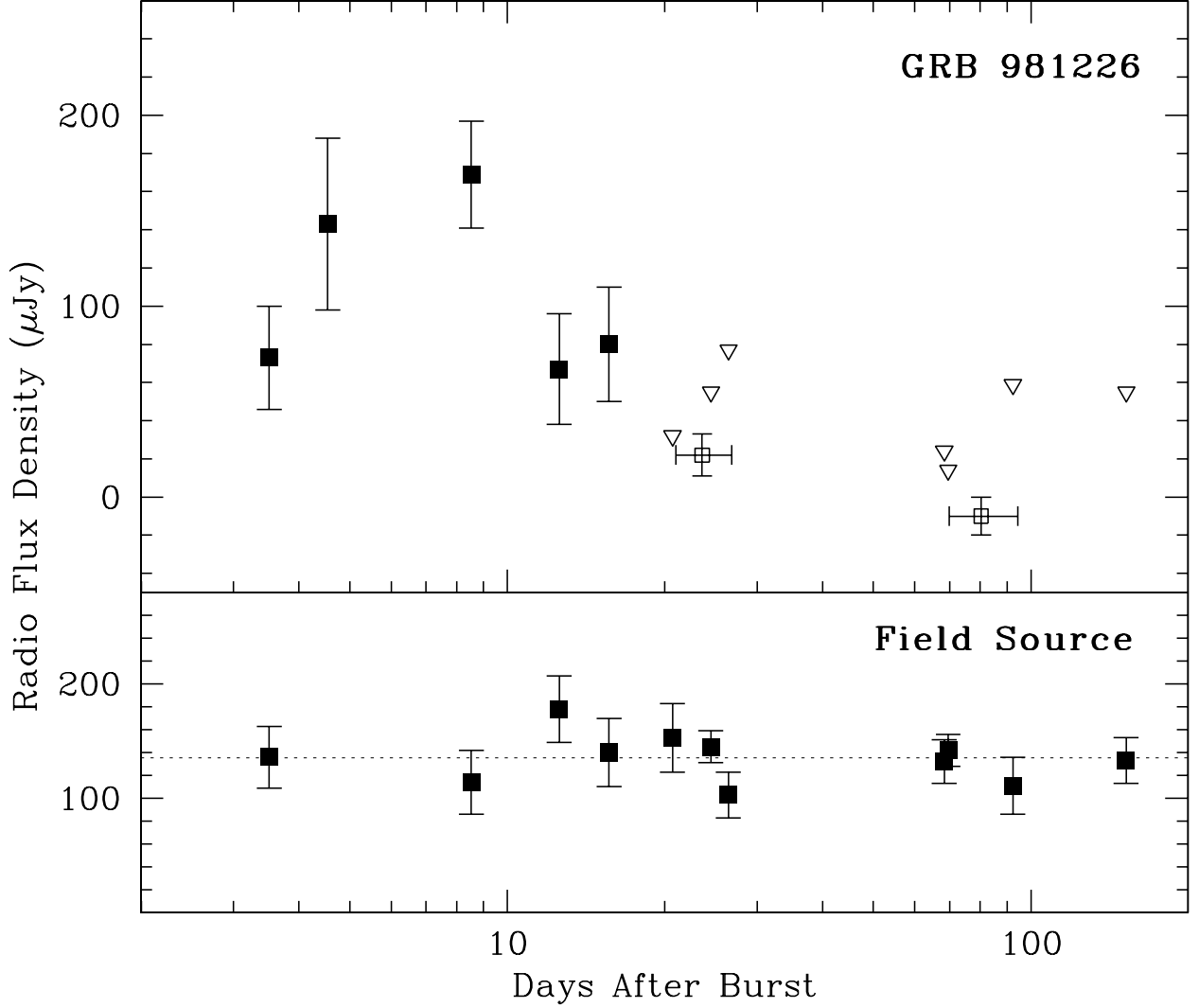
Fig. 2.— A 8.46 GHz light curve of the radio transient of GRB 981226 (top panel), and a background source in the field (bottom panel). Detections at each epoch are indicated by the filled squares. Non-detections are given the open triangles, defined as the peak brightness at the location of VLA J232937.2−235553 plus two times the rms noise in the image. The peak brightness for weighted averages of three adjacent epochs are shown by open squares.
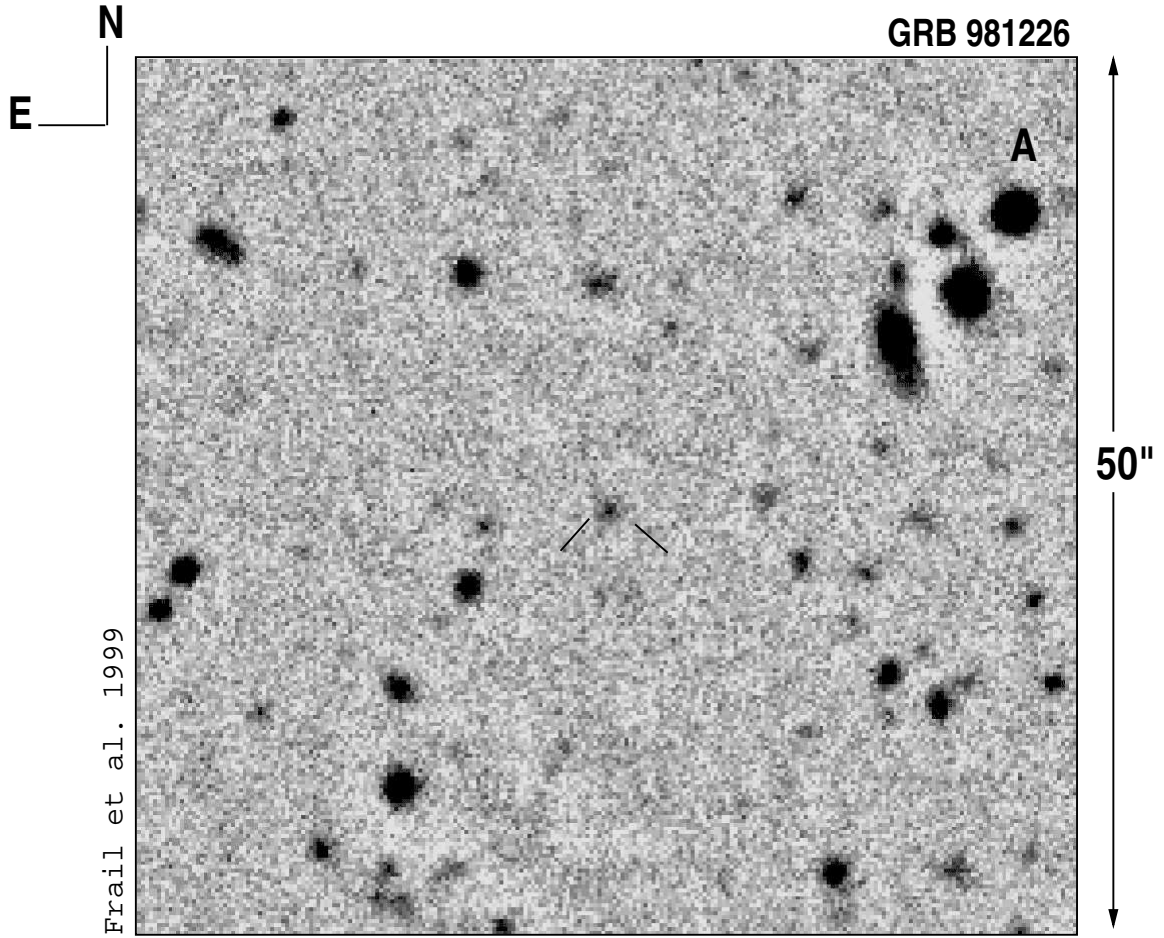
Fig. 3.— Deep optical image of the field centered on the radio afterglow of GRB 981226. This 3360-s R-band exposure on the Keck II 10-m LRIS (Oke et al. 1995) instrument reveals a faint galaxy coincident (within the astrometric errors) with R = 24.85 ±0.06. Star "A" is labeled as a photometric reference (see text).